

# Prompt dipole radiation in fusion reactions

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The prompt  $\gamma$ -ray emission was investigated in the 16A MeV energy region by means of the  $^{36,40}\text{Ar}+^{96,92}\text{Zr}$  fusion reactions leading to a compound nucleus in the vicinity of  $^{132}\text{Ce}$ . We show that the prompt  $\gamma$  radiation, which appears to be still effective at such a high beam energy, has an angular distribution pattern consistent with a dipole oscillation along the symmetry axis of the dinuclear system. The data are compared with calculations based on a collective bremsstrahlung analysis of the reaction dynamics.

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The study of the Giant Dipole Resonance (GDR) decay from excited nuclei is a topic of central importance in nuclear physics because it constitutes a powerful probe to get insight into the features of nuclei far from normal conditions. It was suggested many years ago in [1] that the charge equilibration mechanism occurring in dissipative heavy-ion collisions could be related to the direct excitation of a GDR in the composite system. Subsequently, this idea was considered within various theoretical frameworks ([2, 3, 4, 5, 6], [7] and references therein) leading to similar conclusions: at the very early stages of charge-asymmetric heavy-ion collisions a large amplitude collective dipole oscillation, the so-called dynamical dipole mode, can be triggered along the symmetry axis of the strongly deformed composite system. This oscillation could decay emitting prompt dipole photons, in addition to the photons originating from the GDR thermally excited in the hot compound nucleus (CN), with: i) a lower energy than that of a GDR built in a spherical nucleus of similar mass and ii) an anisotropic angular distribution. Different parameters are predicted to influence the prompt dipole photon intensity: besides the entrance channel charge asymmetry also the mass asymmetry [7] and the incident energy [2, 4, 7] should play a role.

From an experimental point of view there have been attempts [8, 9, 10, 11, 12, 13] to evidence this pre-equilibrium emission by using the following technique: formation of the same composite system from entrance channels with different charge asymmetry. The comparison of the associated  $\gamma$ -ray spectra in the above measurements evidenced an excess in the composite system

GDR energy region for the more charge asymmetric system that was identified with the prompt dipole radiation. However, to date no experimental information exists on the angular distribution of this  $\gamma$ -ray excess that allows to draw firm conclusions on its origin. Furthermore, there is no systematic study of the phenomenon as a function of the reaction parameters that are predicted to influence it.

In our previous works [10, 11] we started an investigation of the prompt dipole radiation for the  $^{32,36}\text{S}+^{100,96}\text{Mo}$  reaction pair at incident energies  $E_{\text{lab}}=6\text{A}$  and  $9\text{A}$  MeV. In these measurements, a CN in the Ce mass region was formed with excitation energy  $E^*=117$  and  $174$  MeV, respectively. In the present letter we extend our investigation by using the  $^{36}\text{Ar}+^{96}\text{Zr}$  and  $^{40}\text{Ar}+^{92}\text{Zr}$  reactions at  $E_{\text{lab}}=16$  and  $15.1\text{A}$  MeV, respectively, to form a CN in the same mass region (average mass  $A\sim 126$ ) at an average excitation energy  $E^*\sim 280$  MeV. We present the first experimental evidence that the prompt radiation is related to a dipole oscillation along the dinuclear system symmetry axis, by studying its angular distribution. We infer the characteristics of this oscillation and their dependence on beam energy. Finally, we compare our data with calculations based on a collective bremsstrahlung analysis of the reaction dynamics.

All the studied reaction pairs leading to compound nuclei in the Ce mass region are presented in Table I, along with the entrance channel relevant quantities, i.e. the incident energy, the CN excitation energy, the initial dipole moment  $D(t=0)$  and the mass asymmetry  $\Delta$  (for a defini-

TABLE I: Reaction pair, incident energy, compound nucleus excitation energy, initial dipole moment  $D(t=0)$ , initial mass asymmetry  $\Delta$ , percent increase of the intensity in the linearized  $\gamma$ -ray spectra for the more charge asymmetric system (the energy integration limits, in MeV, are given in the parenthesis), centroid energy  $E_{dd}$  and width  $\Gamma_{dd}$  of the dynamical dipole mode obtained by the fit of the data described in the text.

Reaction	$E_{lab}$ (MeV/nucleon)	$E^*$ (MeV)	$D(t=0)$ (fm)	$\Delta$	Increase (%)	$E_{dd}$ (MeV)	$\Gamma_{dd}$ (MeV)	Ref
$^{32}\text{S}+^{100}\text{Mo}$	6.125	117	18.2	0.19	$1.6 \pm 2.0$ (8,21)			[11]
$^{36}\text{S}+^{96}\text{Mo}$	5.95	117	1.7	0.16				
$^{32}\text{S}+^{100}\text{Mo}$	9.3	174	18.2	0.19	$25 \pm 2$ (8,21)	$11.4 \pm 0.3$	$3.0 \pm 0.5$	[10]
$^{36}\text{S}+^{96}\text{Mo}$	8.9	174	1.7	0.16				
$^{36}\text{Ar}+^{96}\text{Zr}$	16	$\sim 280$	20.6	0.16	$12 \pm 2$ (8,21)	$12.2 \pm 0.6$	$3.7 \pm 1.4$	present data
$^{40}\text{Ar}+^{92}\text{Zr}$	15.1	$\sim 280$	4.0	0.14				

tion of the dipole moment and mass asymmetry see [11]). The technique used in the present work is the same described in [10, 11], that is all reaction parameters were identical for the two systems apart from the initial dipole moment. From Table I we can see that the dipole moment changed by 16.6 fm from the  $^{40}\text{Ar} + ^{92}\text{Zr}$  system to the more N/Z asymmetric one,  $^{36}\text{Ar} + ^{96}\text{Zr}$ , while the entrance channel mass asymmetry changed by a very small amount. The critical angular momentum for fusion events was equal for both reactions, according to PACE2 calculations [14], avoiding thus any difference in the CN spin distribution. Moreover, the CN excitation energy was the same within errors in both reactions as it will be shown later in the text. The results concerning the  $^{36,40}\text{Ar} + ^{96,92}\text{Zr}$  pair can be directly compared with those related to the  $^{32,36}\text{S}+^{100,96}\text{Mo}$  one because of the similar difference in the entrance channel dipole moment and mass asymmetry.

The  $^{36,40}\text{Ar}$  pulsed beams, provided by the Superconducting Cyclotron of the Laboratori Nazionali del Sud (LNS), impinged on a  $450 \mu\text{g}/\text{cm}^2$ -thick  $^{96}\text{ZrO}_2$  and on a  $600 \mu\text{g}/\text{cm}^2$ -thick  $^{92}\text{ZrO}_2$  target enriched to 95.63% in  $^{96}\text{Zr}$  and to 95.36% in  $^{92}\text{Zr}$ , respectively. The targets were evaporated on carbon layers 90 and  $60 \mu\text{g}/\text{cm}^2$ -thick, respectively. The  $\gamma$ -rays ( $E_\gamma > 5.5$  MeV) and the light charged particles were detected by using the 180 BaF<sub>2</sub> modules of the MEDEA experimental apparatus [15] that covers the polar angular range between  $\theta=30^\circ$  and  $\theta=170^\circ$  and the full range in the azimuthal angle  $\phi$ . The fusion-evaporation residues were detected by four Parallel Plate Avalanche Counters (PPAC's) located symmetrically around the beam direction at 70 cm from the target, centered at  $\theta=7^\circ$  and covering  $7^\circ$  in  $\theta$ . They provided the time of flight with respect to the radiofrequency signal of the accelerator and the energy loss of the reaction products. Down-scaled single events together with coincidence events between a PPAC and at least one fired BaF<sub>2</sub> scintillator were collected during the experiment. The energy calibration of the  $\gamma$ -ray detectors was obtained by using the composite radioactive sources of  $^{241}\text{Am}+^9\text{Be}$  and  $^{238}\text{Pu}+^{13}\text{C}$  and the 15.1

MeV  $\gamma$ -rays from the  $p+^{12}\text{C}$  reaction while the calibration of the charged particles was performed as described elsewhere [16]. The discrimination between  $\gamma$ -rays, light charged particles and neutrons was performed by combining a pulse shape analysis of the BaF<sub>2</sub> signal and a time of flight measurement with respect to the radiofrequency signal of the Cyclotron.

At the present incident energies, the incomplete fusion cross section represents approximately the 90% of the total fusion cross section [17]. The average excitation energy and the average mass carried away by the pre-equilibrium particles was evaluated by analyzing the energy spectra of the protons and alpha particles detected at different angles in coincidence with the evaporation residues. The particle spectra were simultaneously fitted in the hypothesis of two moving sources (see for example [18]). A slow source having the center-of-mass velocity which simulates the statistical particle emission from the CN and an intermediate-velocity source that represents the emission of fast particles of non statistical origin. Details on this analysis will be presented elsewhere. The relevant information extracted from the above work concerns the CN average excitation energy and average mass that was found to be identical within errors for the two reactions. This allows us to compare safely the associated  $\gamma$ -ray spectra with each other. The CN excitation energy estimated from our data (see Table I) is somewhat lower than that predicted by the empirical formula given in [19] for the  $^{18}\text{O}+^{100}\text{Mo}$  system, according to which, the excitation energy in the present case is expected to be  $E^* \sim 300$  MeV.

In Fig.1a we present the bremsstrahlung-subtracted  $\gamma$ -ray spectra of the  $^{40}\text{Ar}+^{92}\text{Zr}$  (open circles) and  $^{36}\text{Ar}+^{96}\text{Zr}$  (filled squares) reaction, taken at  $\theta=90^\circ$  in coincidence with the evaporation residues and integrated over  $4\pi$  assuming an isotropic angular distribution.  $\epsilon_{det}$  is the energy dependent efficiency of the experimental apparatus. The bremsstrahlung component was deduced by fitting simultaneously the  $\gamma$ -ray spectra of both reactions for  $E_\gamma \geq 35$  MeV at different angles by means of an exponential function with isotropic emission in a reference frame

moving with  $0.5v_{beam}$  [20]. The difference between these spectra, displayed in the same figure with the stars, shows an excess of  $\gamma$ -rays emitted during the charge asymmetric reaction ( $^{36}\text{Ar}+^{96}\text{Zr}$ ) and concentrated at  $E_\gamma \sim 12$  MeV, that is in the energy region of the CN GDR. This excess is related to entrance channel charge asymmetry effects, being identical all the other reaction parameters and it is attributed to the dynamical dipole mode present at the beginning of the dinuclear system formation. To deduce the centroid energy  $E_{dd}$  and the width  $\Gamma_{dd}$  of the dynamical dipole mode, the observed  $\gamma$ -ray excess was fitted by means of a lorentzian curve folded by the experimental apparatus response function (solid line of Fig. 1a) [21]. The parameters extracted from the fit are seen in Table I for both the present data and the data taken at 9A MeV. For both beam energies,  $E_{dd}$  was found to be lower than the centroid energy of the CN GDR ( $E_{GDR}=14$  MeV), implying a deformation of the composite system at the moment of the prompt dipole  $\gamma$ -ray emission. In a naive picture of two colliding nuclei at the touching configuration, we expect  $E_{dd} \sim \frac{78}{A_1^{1/3}+A_2^{1/3}} \sim 10$  MeV,  $A_1$  and  $A_2$  being the colliding ion masses. The fact that it was found to be somewhat larger than that expected, nicely confirms that some density overlap already exists at the start up of the dipole oscillation [6]. It is interesting to notice from Table I that centroid energy and width remain constant within errors by increasing the beam energy.

The details in the GDR energy region can be better evidenced if the  $\gamma$ -ray spectra of Fig. 1a are linearized, dividing them by the same theoretical spectrum. This theoretical spectrum was obtained by using the statistical decay code CASCADE [22] with a constant dipole strength function and folded by the response function of the experimental apparatus. The resulting linearized data are shown with the same symbols in Fig. 1b. The solid line in the figure depicts the linearized theoretical  $\gamma$ -ray spectrum of the charge symmetric reaction calculated with the CASCADE code and folded by the experimental setup response function. For the calculation, the following parameters were used: a CN mass  $A=126$ ,  $E^*=284$  MeV and a level density parameter which varies with nuclear temperature according to ([23] and ref. 26 therein). The GDR strength function was taken to be a lorentzian curve with centroid energy  $E_{GDR}=14$  MeV, width  $\Gamma_{GDR} = 13$  MeV and strength  $S_{GDR}=100\%$  of the E1 energy-weighted sum-rule strength. Moreover, a cut-off in the  $\gamma$ -ray emission for excitation energies larger than  $E^*=250$  MeV was applied, in good agreement with [24] for nuclei in the  $A \sim 115$  mass region.

If the linearized data of Fig. 1b are integrated between 8 and 21 MeV, an increase of the  $\gamma$ -ray intensity of 12% is found in the more charge asymmetric system. From Table I, where the percent increase of the linearized spectra for the three beam energies is shown, we can see that the prompt dipole radiation intensity presents a maximum

at 9A MeV decreasing toward lower and higher energies. Although diminished with respect to its value at 9A MeV, it is still observed at nuclear excitation energies as high as  $\sim 280$  MeV, excluding a fast increase of the dynamical dipole mode damping width with excitation energy. In fact the dynamical dipole mode is a pre-equilibrium collective oscillation present before the thermalization of the mechanical energy. The damping is then also related to fast processes, the pre-equilibrium nucleon emissions (mostly neutrons, that are reducing the asymmetry) and (p,n) direct collisions that will damp the isovector oscillation. From calculations we expect that both mechanisms are smoothly increasing in the present range of beam energies.

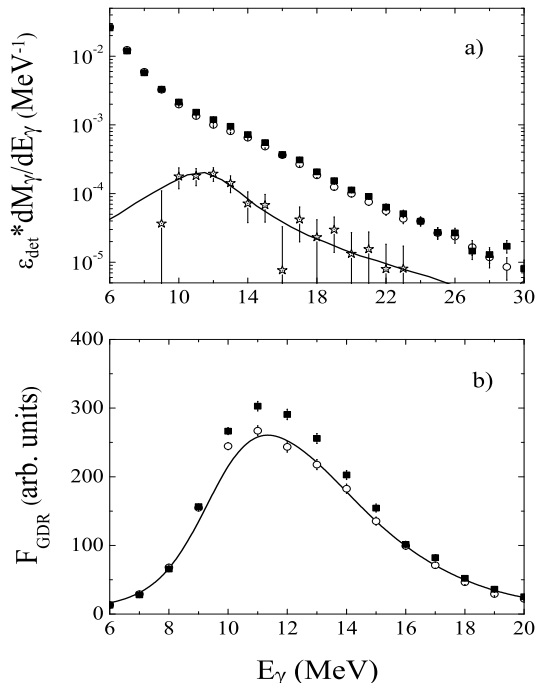


FIG. 1: a) 90° bremsstrahlung-subtracted  $\gamma$ -ray spectrum of the  $^{36}\text{Ar}+^{96}\text{Zr}$  (filled squares) and the  $^{40}\text{Ar}+^{92}\text{Zr}$  (open circles) reaction in coincidence with evaporation residues along with their difference (stars). The solid line is the result of the fit described in the text. b) 90° bremsstrahlung-subtracted linearized  $\gamma$ -ray spectra. The solid line represents the linearized theoretical spectrum calculated with the code CASCADE for the charge symmetric reaction.

Up to now, experimental evidences of the dipole character of the prompt  $\gamma$ -ray emission have never been reported in the literature. To infer it, we display in Fig. 2 the center-of-mass angular distribution with respect to the beam direction of the observed  $\gamma$ -ray excess, integrated over energy from 10 to 15 MeV. The lines in the figure depict the expected angular distribution given by the Legendre polynomial expansion:  $W(\theta_\gamma) = W_0[1 + a_2 P_2(\cos(\theta_\gamma))]$  for different values of the anisotropy coefficient  $a_2$ . In all cases, the coefficient  $W_0$  was obtained from a best fit to the data. When  $a_2 = -1$  the angular distribution takes the  $\sin^2(\theta_\gamma)$  form of pure

dipole emission (solid line), while  $a_2 = -0.8$  (dashed line) and  $a_2 = -0.5$  (dotted line) correspond to more diffuse angular distributions. We see that the experimental angular distribution is strongly anisotropic with a maximum around  $90^\circ$ , consistent with emission from a dipole oscillating along the beam axis (solid line). For near-central collisions as in the present case, the symmetry axis of the dinuclear composite system is nearly coincident with the beam axis at the very early moments of its formation. In the case of a larger mean inclination of the axis of the direct dipole oscillation because rotation has taken place meanwhile, we would expect a widening of the angular distribution with respect to  $90^\circ$  (dashed and dotted lines). This effect should be directly related to: a) the rotation angular velocity of the dinuclear system during the prompt dipole emission b) the instant at which this emission occurs. The data suggest that the oscillation axis of the direct dipole has not rotated much with respect to the beam direction. This result is compatible with emission of the prompt dipole radiation at the very beginning of the reaction. In perspective, we can say that accurate measurements of the dynamical dipole angular distribution could even allow to directly evaluate the corresponding mean rotation of the emitting dinuclear system and so the time scale of such pre-equilibrium  $\gamma$  radiation.

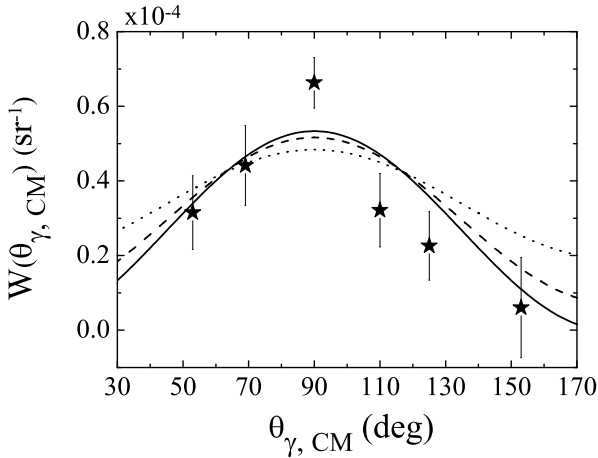


FIG. 2: Center-of mass angular distribution of the difference between the data of the two reactions for  $\gamma$ -rays with  $10 \text{ MeV} \leq E_\gamma \leq 15 \text{ MeV}$ . The lines are described in the text.

Calculations of the prompt dipole radiation for the  $^{36}\text{Ar} + ^{96}\text{Zr}$  and  $^{32}\text{S} + ^{100}\text{Mo}$  reactions at 16A MeV were performed within the BNV transport model framework and based on a collective bremsstrahlung approach [7, 11, 25]. In the transport calculations no free parameters were used. The results for the above reactions are identical within a 20% uncertainty, justifying thus their direct comparison with each other. For near-central collisions the total multiplicity of the prompt dipole radiation was found to be  $0.8 \cdot 10^{-3}$  and  $1.4 \cdot 10^{-3}$ , depending on the NN cross section used. The lower estimation is related to

free NN cross sections, while the upper one is obtained with the in medium reduced ones [26]. Reduced cross sections are leading to larger dipole radiation rates for two reasons: i) less fast nucleons emission, in particular for neutrons which directly decrease the dipole strength; ii) reduced attenuation of the dipole p-n oscillation due to a smaller number of p-n direct collisions. The theoretical total multiplicity is in very good agreement with the experimental one,  $(0.7 \pm 0.1) \cdot 10^{-3}$ , obtained integrating the  $\gamma$ -ray excess over energy and over solid angle by taking into account its angular distribution and the experimental set up efficiency. Moreover, the theoretical dynamical dipole centroid energy and width,  $E_{dd,th} \sim 9 \text{ MeV}$  and  $\Gamma_{dd,th} \sim 2 \text{ MeV}$ , are in reasonable agreement with the corresponding experimental values (Table I).

In summary, we present a study of the prompt dipole radiation in the 16A MeV energy region and we compare the present results with previous ones obtained at lower incident energy. The outstanding feature of our data is the angular distribution pattern of the observed  $\gamma$ -ray excess which is consistent with that of a dipole oscillating along the beam axis. This result suggests that the prompt  $\gamma$ -ray emission occurs during the first stages of the dinuclear system formation. Calculations based on a collective bremsstrahlung analysis of the reaction dynamics predict characteristics of the dynamical dipole mode that are in good consistency with experiment.

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